Chemical Evolution

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A. McWilliams

Chemical Evolution of the Galaxy

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AN INTRODUCTION TO GALACTIC CHEMICAL EVOLUTION

Nikos Prantzos

Conference: Stellar Nucleosynthesis: 50 years after B2FH

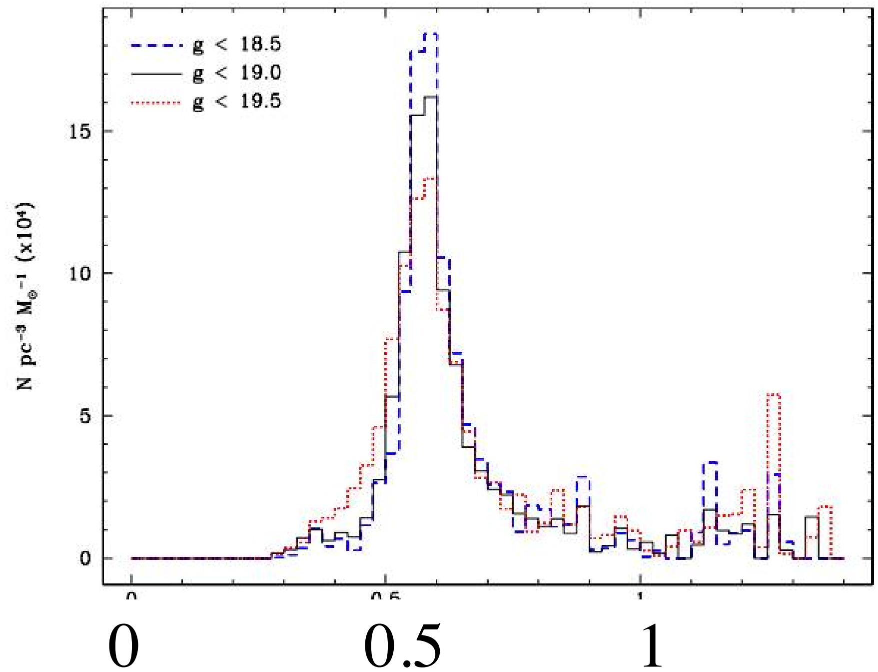
Review sec 10.4 of MBW

- Hydrogen, helium, and traces of lithium, boron, and beryllium were produced in the Big Bang.
- All other elements (i.e. all other "metals") were created in Stars by nucleosynthesis
- Gas is transformed into stars.
- stars burns hydrogen and helium in their cores and produce 'heavy' elements.
- These elements are partially returned into the interstellar gas at the end of the star's life via stellar winds, planetary nebulae or supernovae explosions.
- Some fraction of the metals are locked into the remnant (NS, BH or WD) of the star.
- If there is no gas infall from the outside or loss of metals to the outside, the metal abundance of the gas, and of subsequent generations of stars, should increase with time.
- So in principle the evolution of chemical element abundances in a galaxy provides a clock for galactic aging.
  - One should expect a relation between metal abundances and stellar ages.
  - On average, younger stars should contain more iron than older stars. This is partially the case for the solar neigborhood, where an age-metallicity relation is seen for nearby disk stars, but a lot of scatter is seen at old ages (> 3 Gyr; e.g., Nordstrom, Andersen, & Mayor 2005).
- Clearly, our Galaxy is not so simple need to add a few more ingredients to better match

the observations

Quick review of Metal Production

- following MBW (10.4.1)
- At $M<8M_\odot$; stars end life as CNO WDs- mass distribution of WDs is peaked at $M\sim0.6\ M_\odot$ so they must lose mass-
- for SNIa to have exploded today, needed to have formed WD, so need evolution time <age of system; e.g. for 1Gyr old system $3M_\odot < M < 8M_\odot$



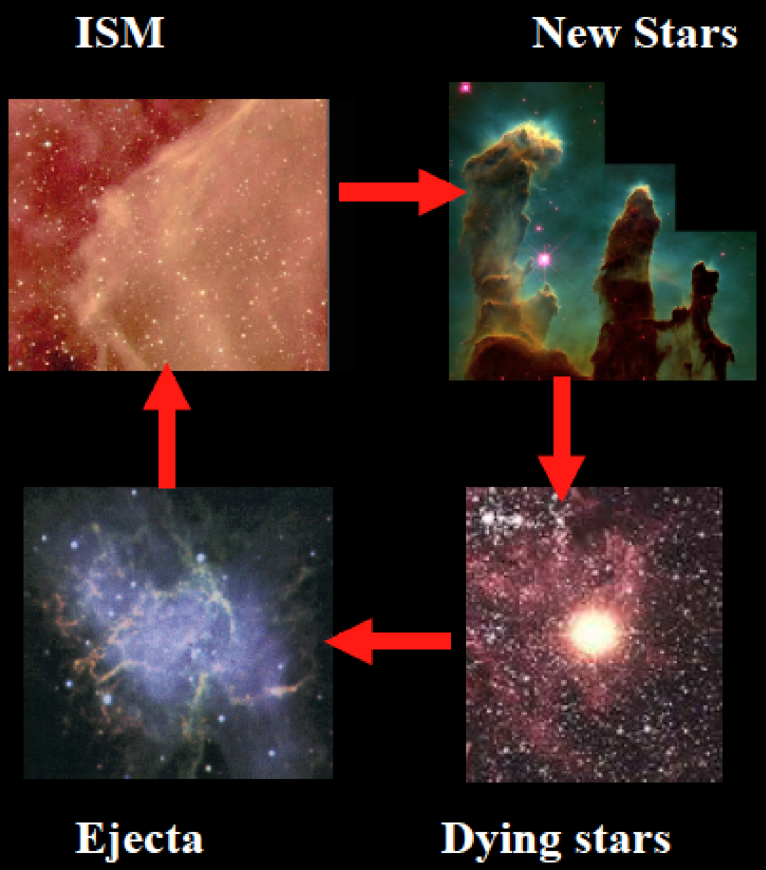
White dwarf mass function DeGennaro et al 2008

- SNIa ; no good understanding of the stellar evolutionary history of SNIa- must produce 'most' of Fe and significant amounts of Si,S,Ca, Ar
- Production of C, N not primarily from SN

•At $M>8M_\odot$; Explosion of massive stars (Type II and SNIb) Oxygen and the α-elements (Ne,Mg,...)

Cycle of GAS and STARS in Galaxies

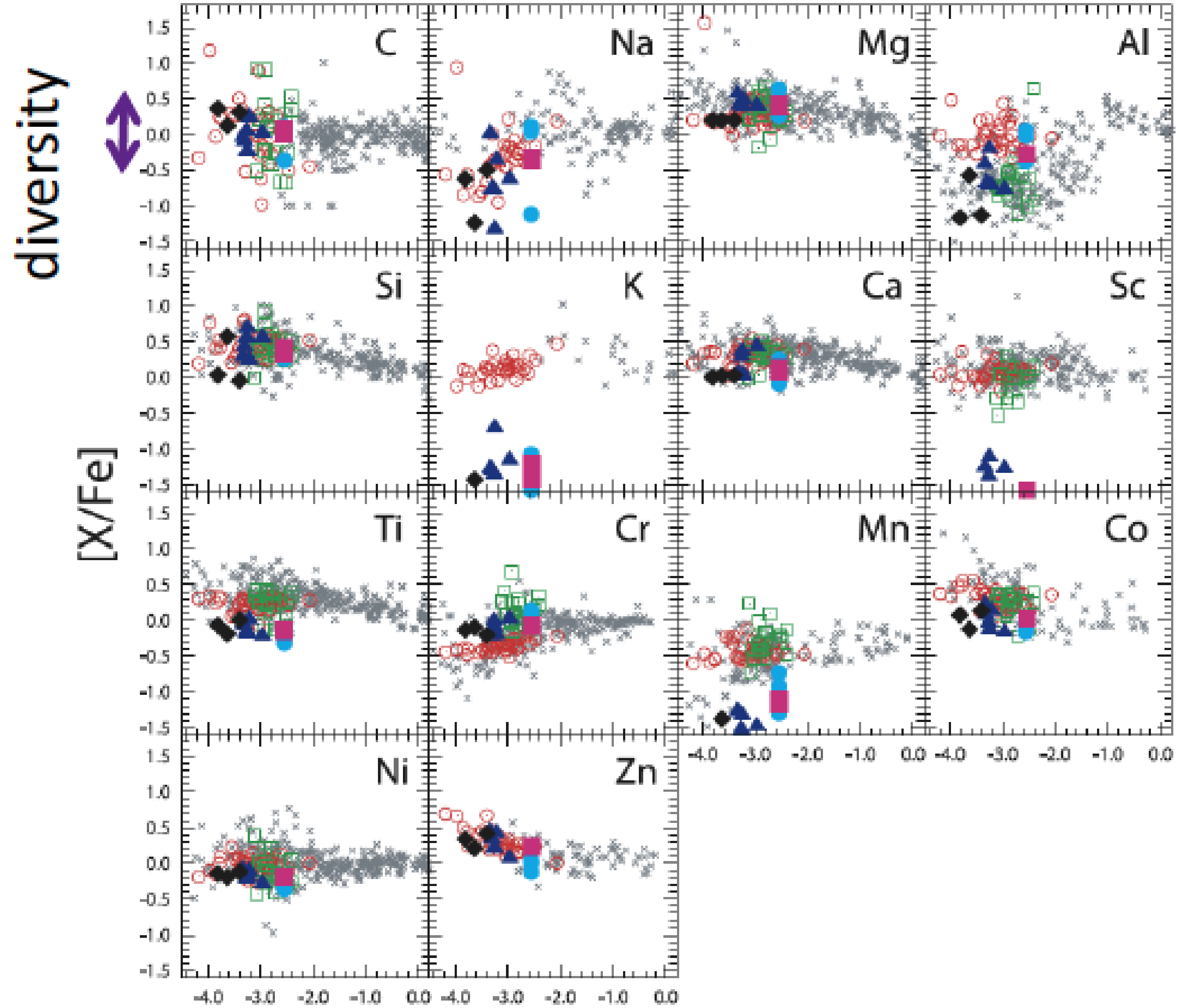
- *Gas is transformed into stars*
- *Each star burns H and He in its nucleus and produces heavy elements*
- *These elements are partially returned into the interstellar gas at the end of the star's life*
  - *Through winds and supernovae explosions*
  - *Some fraction of the metals are locked into the remnant of the star*



This implies that the chemical abundance of the gas in a star-forming galaxy should evolve with time

Stars in MW

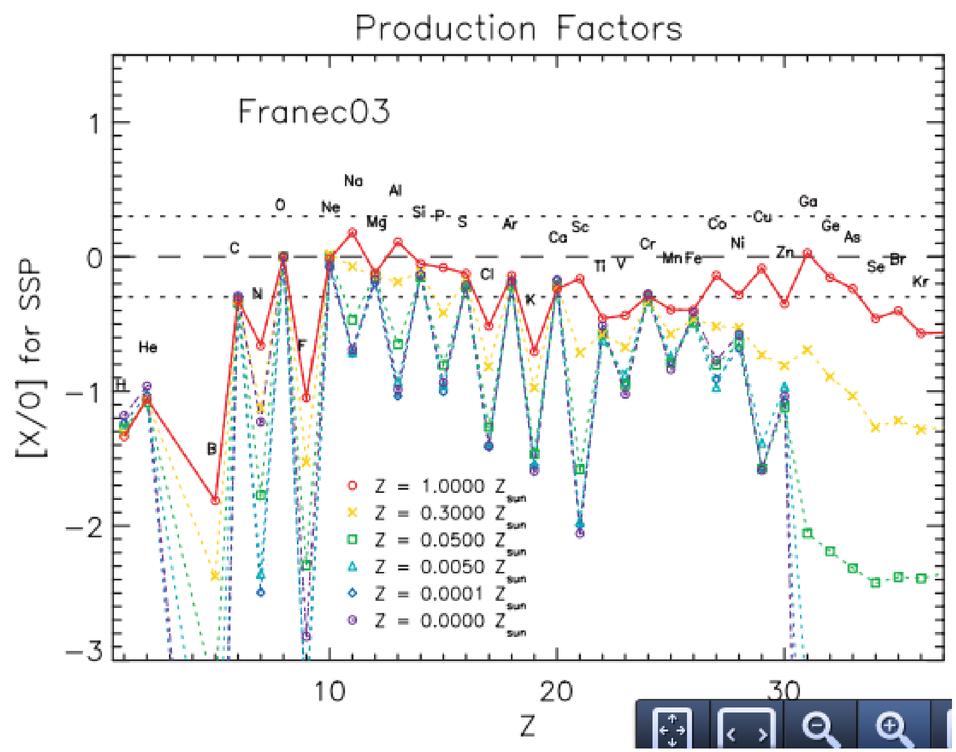
- The type of data that one has to match with a model of metallicity evolution
  - many elements each one has a range of paths for its creation



Metallicity trends of stars in MW
Tomagawa et al 2007

Yield From A SSP

- The yield from massive star SN is a function of intial metallicity (Gibson et al 2003)
- Produce 'solar' abundance of O.... Fe If the initial metallicity is solar (hmmm)



Yield sensitive to upper mass limit (30%)

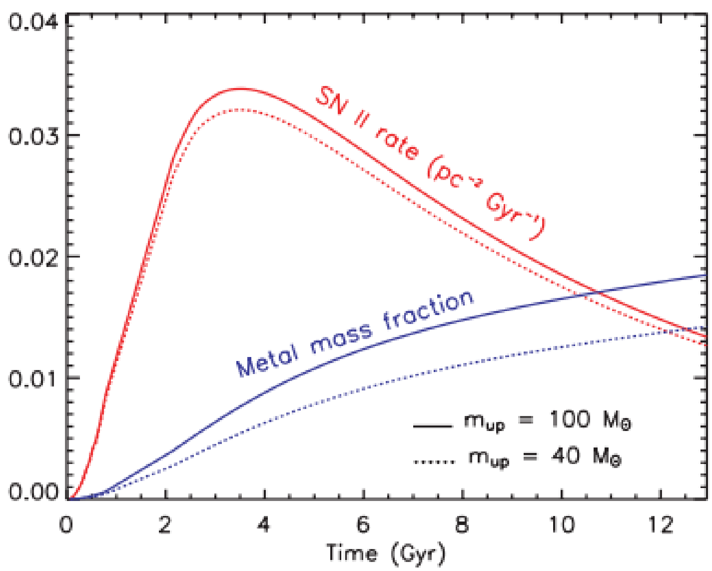
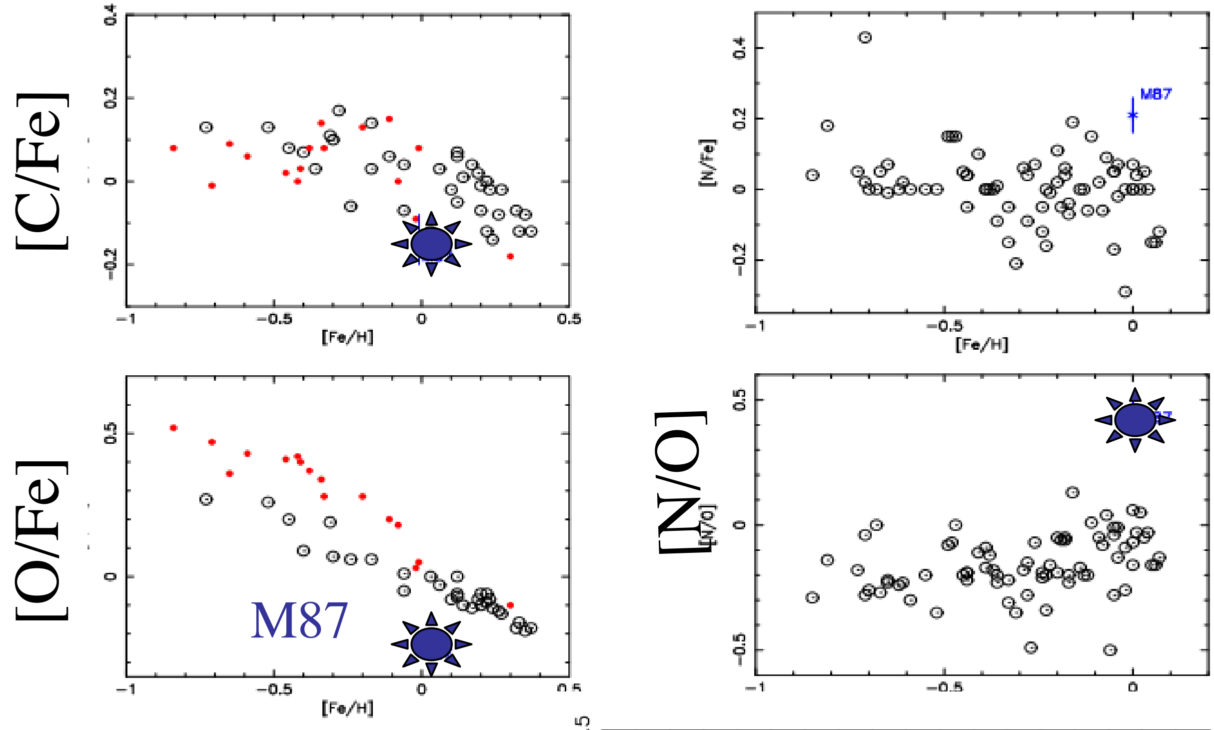
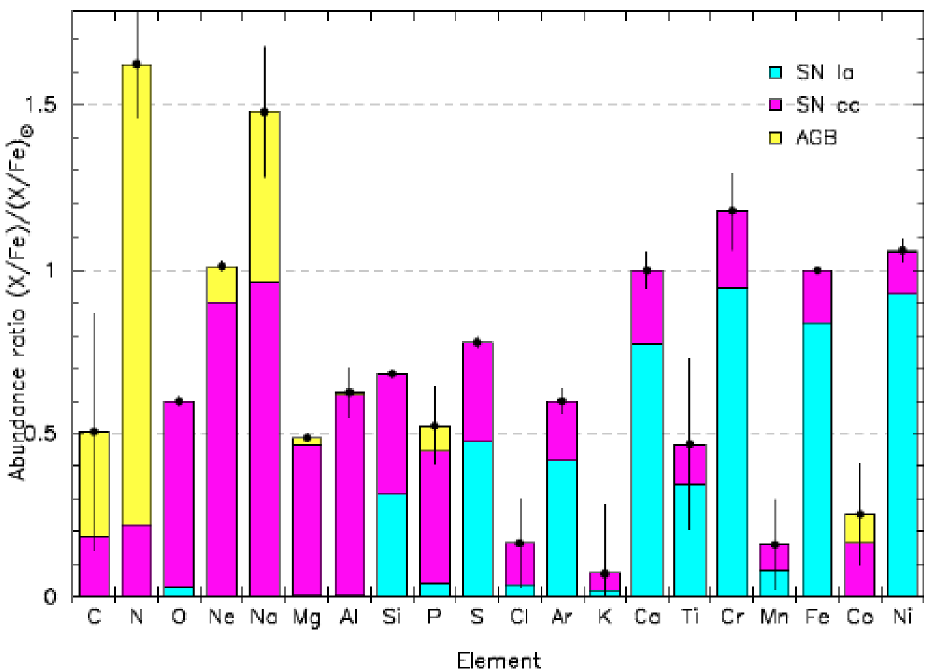


Figure 4 Evolution of Type II SN rate (red lines) and metallicity (blue lines) predicted by a single infall phase model of the solar

Clusters of Galaxies

- In clusters of galaxies 80% of the baryons are in the hot gas
- The abundances of ~8 elements can be well determined
- Abundance ratios do not agree with MW stars





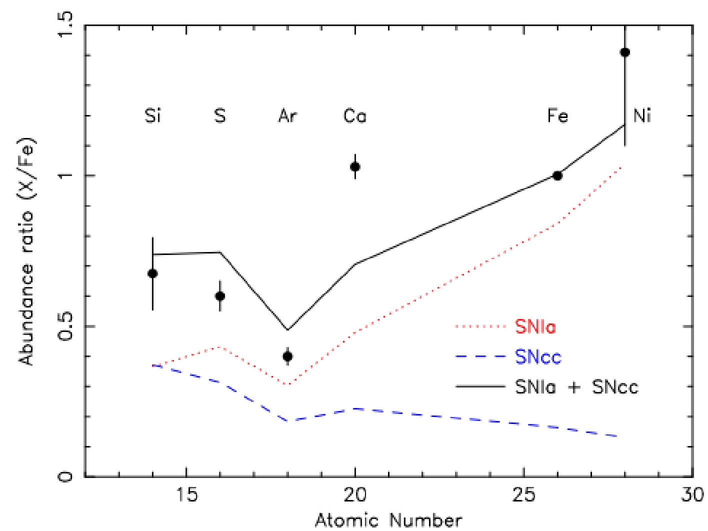


Fig. 4 Abundance ratios fitted with supernova yields from the WDD2 SNIa model (Iwamoto et al. 1999) and a SNcc model with an initial metallicity $Z = 0.02$ and a Salpeter IMF. The calcium abundance appears to be underestimated.

Clusters of Galaxies-Problems

- If one tries to match the Fe abundance in the IGM, the mass in stars today and the metallicity of the stars with a 'normal' IMF one fails by a factor of ~2 to produce enough Fe
- Need a 'bottom heavy IMF' and more type Ia's then seen in galaxies at low z.
- (see Loewenstein 2013- nice description for inverting data to get a history of SF)
-

see MBW sec 11.8 Chemical Evolution of Disk Galaxies

One Zone- Closed Box-See MBW sec 10.4.2

McWilliams 1997

- The model assumes evolution in a closed system,
- generations of stars born out of the interstellar gas (ISM).
- In each generation, a fraction of the gas is transformed into metals and returned to the ISM;
- the gas locked up in long-lived low-mass stars and stellar remnants no longer takes part in chemical evolution.
- Newly synthesized metals from each stellar generation are assumed to be instantaneously recycled back into the ISM and instantaneously mixed throughout the region;
- thus, in this model,
  - metallicity always increases with time, and the region is perfectly homogeneous at all times.
  - the metallicity of the gas (ISM) is determined by the metal yield and the fraction of gas returned to the ISM

Terms

- The ratio of mass of metals ejected to mass locked up, y, is a quantity commonly called the yield of a given element
- If evolution continues to gas exhaustion (e.g. a SSP), then the Simple model predicts that the average mass fraction of metals of long-lived stars is equal to the yield,
  - $\langle Z \rangle = y$. Where Z is the metallicity-**the fraction by mass of heavy elements**
- the total baryonic mass of the box is, $M_{baryons} = M_{g(as)} + M_{s(tar)} =$ constant.

(the Sun's abundance is $Z_{\odot} \sim 0.02$ and the most metal-poor stars in the Milky Way have $Z \sim 10^{-4} Z_{\odot}$),

- the mass of heavy elements in the gas $M_h = ZM_g$
- total mass made into stars is dM'_{star}
- the amount of mass instantaneously returned to the ISM (from supernovae and stellar winds, enriched with metals) is dM''_{star}
- then the net matter turned into stars is $dMs = dM'_s - dM''_{star}$
- mass of heavy elements returned to the ISM is ydM'_{star}
- As you calculated in homework the mass of stars more massive than ~8M is ~0.2 of the total mass assume
  - that this is all the mass returned (ignoring PN and red giant winds)
  - that the average yield is ~0.01
  - the average metallicity of that gas Z~2.5

Closed Box Approximation-Tinsley 1980, Fund. Of Cosmic Physics, 5, 287-388 (see MBW sec 10.4.2).

- To get a feel for how chemical evolution and SF are related (S+G q 4.13-4.17)- but a different approach (Veilleux 2010)

- at time t, mass ΔM_{total} of stars formed, after the massive stars die left with $\Delta M_{low\ mass}$ which live 'forever',
- massive stars inject into ISM a mass $p\Delta M_{total}$ of heavy elements (p depends on the IMF and the yield of SN- normalized to total mass of stars).
- Assumptions: galaxies gas is well mixed, no infall or outflow, high mass stars return metals to ISM faster than time to form new stars)

$M_{total}=M_{gas}+M_{star}$=constant ($M_{baryons}$) ; $M_h$mass of heavy elements in gas $=ZM_{gas}$

dM'_{stars} =total mass made into stars, dM''_{stars} =amount of mass instantaneously returned to ISM enriched with metals

$dM_{stars}=dM'_{stars}-dM''_{stars}$ net matter turned into stars

define y as the yield of heavy elements- yM_{star}=mass of heavy elements returned to ISM

Closed Box- continued

- Net change in metal content of gas
- dM_h=y dM_{star} - Z dM_{star}=(y- Z) dM_{star}

- Change in Z since dM_g= -dM_{star} and Z=M_h/M_g then
- d Z=dM_h/M_g -M_h dM_g/M^2_g =(y- Z) dM_{star}/M_g +(M_h/M_g)(dM_{star}/M_g) =ydM_{star} /M_g
- d Z/dt=-y(dM_g/dt) M_g

- If we assume that the yield y is independent of time and metallicity (Z) then

Z(t)= Z_0-y ln $M_g(t)/M_g(0)$= Z_0=yln μ;

μ=gas (mass) fraction Mg(t)/Mg(0)=Mg(t)/Mtot

metallicity of gas grows with time logarithmatically

Closed Box- continued

mass of stars that have a metallicity less than $Z(t)$ is $M_{star}[< Z(t)]=M_{star}(t)=M_g(0)-M_g(t)$
or
$M_{star}[< Z(t)]=M_g(0)*[1-\exp((Z(t)-Z_0)/y]$

when all the gas is gone mass of stars with metallicity $Z, Z+dZ$ is
$M_{star}[Z] \alpha \exp((Z(t)-Z_0)/y)dZ$: use this to derive the yield from observational data

$Z(today)\sim Z_0-y\ln[M_g(today)/M_g(0)]$; $Z(today)\sim 0.7\, Z_{sun}$

since intial mass of gas was the sum of gas today and stars today
$M_g(0)=M_g(today)+M_s(today)$ with $M_g(today)\sim 40M_\odot/pc^2$ $M_{stars}(today)\sim 10M_\odot/pc^2$
get $y=0.43\, Z_{sun}$ see pg 180 S&G to see sensitivity to average metallicity of stars

Metallicity Distribution of the Stars

The mass of the stars that have a metallicity less than Z(t)

is

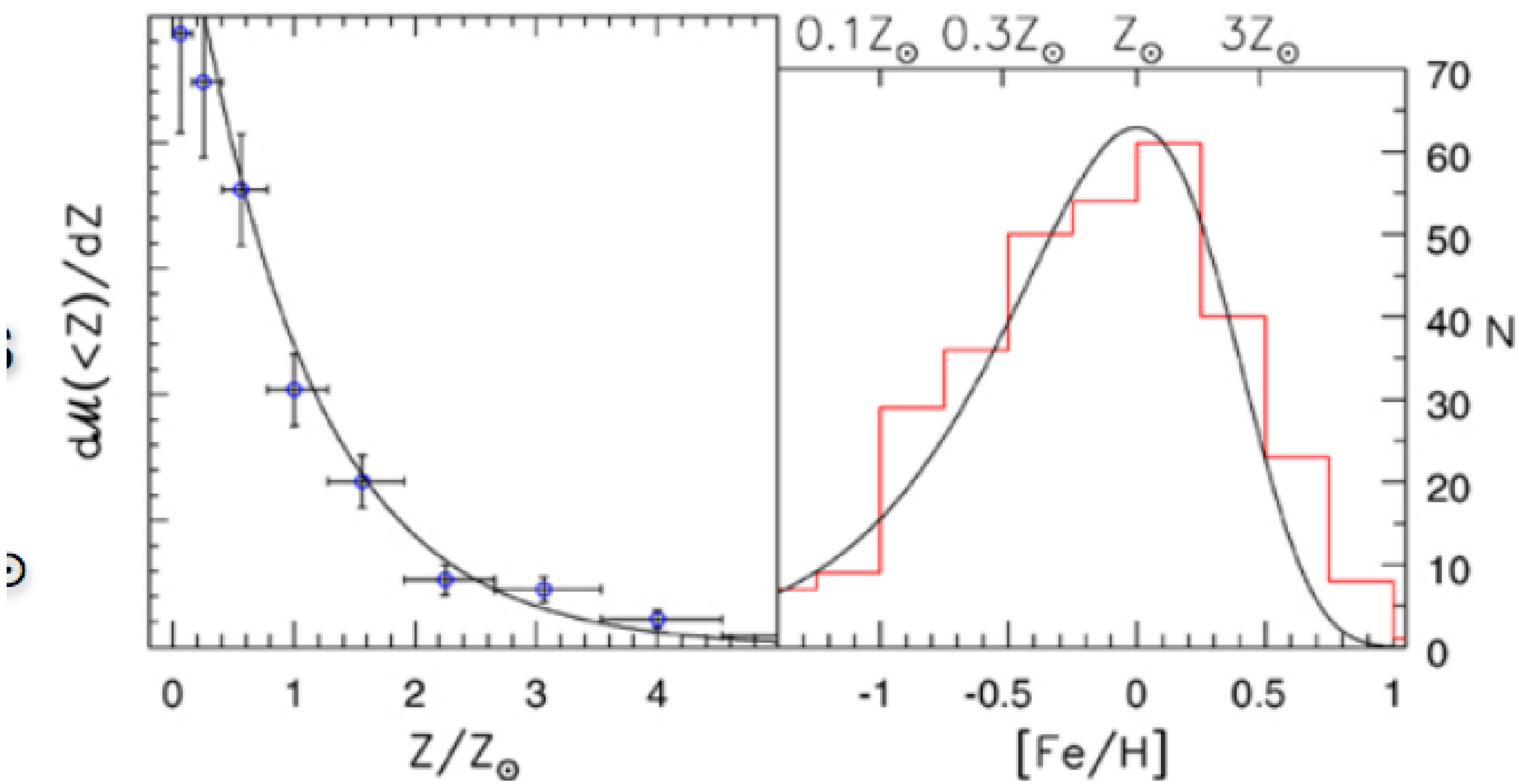
- M_{star} [< Z(t)] = $M_{star}(t) = M_g(0) – M_g(t)$

M_{star} [< Z(t)] =$M_g(0)$*[1 – e –(Z(t)-Z_0)/y]

- When all the gas has been consumed, the mass of stars with metallicity Z, Z + dZ is
- $dM_{star}(Z)$ α exp–[(Z-Z_0)/y] dZ

Closed Box Model- Success

- Bulge giants- fit simple closed box model with complete gas consumption- with most of gas lost from system.
- In the case of complete gas consumption the predicted distribution of abundances is f(z)=(1/<z>)exp(-z/<z>)- fits well (Trager)



G dwarf Problem

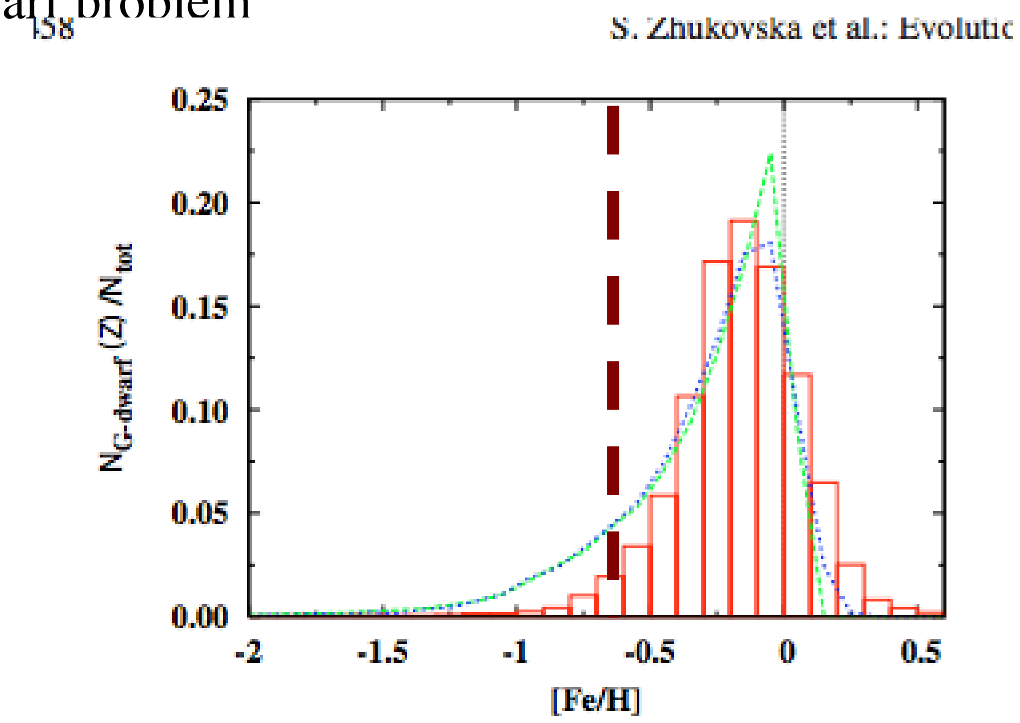
- What should the disk abundance distribution be ?
- the mass in stars with $Z < 0.25\ Z_{sun}$ compared to the mass in stars with the current metallicity of the gas:

$$M_{star}(< 0.25Z_{sun})/M_{star}(< 0.7\ Z_{sun}) = [1- \exp -(0.25\ Z_{sun}/y)]/[1-\exp -(0.7\ Z_{sun}/y)] \sim 0.54$$

- Half of all stars in the disk near the Sun **should** have $Z < 0.25\ Z_{sun}$
- However, only 2% of the F-G (old) dwarf stars in the solar neighborhood have such metallicity

This discrepancy is known as the “G-dwarf problem”

Zhukovska et al CRAL-2006. Chemodynamics: From First Stars to Local Galaxies



Closed Box- Problems

- Problem is that closed box connects today's gas and stars yet have systems like globulars with no gas and more or less uniform abundance.
- Also need to tweak yields and/or assumptions to get good fits to different systems like local group dwarfs.
- Also 'G dwarf' problem in MW (S+G pg 11) and different relative abundances (e.g C,N,O,Fe) amongst stars

- Go to more complex models - leaky box (e.g outflow/inflow); (MBW sec 10.4.3 for details, inflow and outflow models)

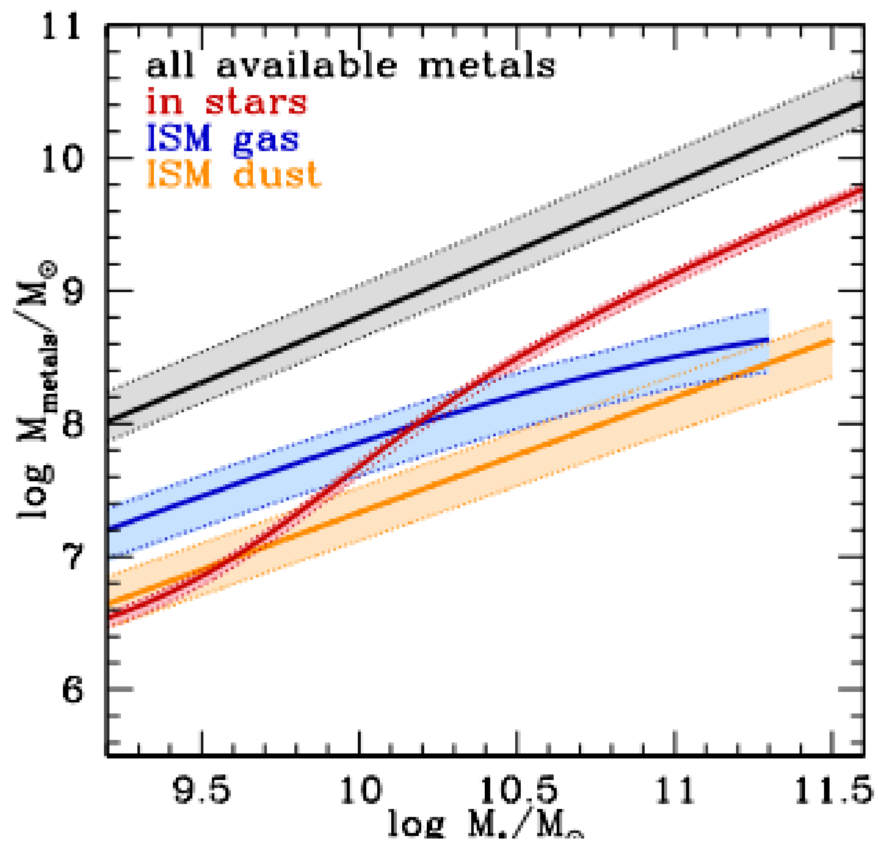
  - assume outflow of metal enriched material g(t); if this is proportional to star formation rate $g(t)=cdM_s/dt$; result is $Z(t)= Z(0)-[(y/(1+c))*\ln[M_g(t)/M_g(0)]$- reduces effective yield but does not change relative abundances

Leaky box

Outflow and/or accretion is needed to explain

- Metallicity distribution of stars in Milky Way disk
- Mass-metallicity relation of local star-forming galaxies
- Metallicity-radius relation in disk galaxies
- Metals in the IGM in clusters and groups

- see arXiv:1310.2253 A Budget and Accounting of Metals at z~0: Results from the COS-Halos Survey Molly S. Peeples, et al



Leaky-Box Model

- If there is an outflow of processed material, $g(t)$, the conservation of mass (Eq. 1) becomes

$$dM_g/dt + dM_s/dt + g(t) = 0$$

- And the rate of change in the metal content of the gas mass (Eq. 2) now becomes

$$dM_h/dt = y\, dM_s/dt - Z\, dM_s/dt - Zg$$

- Example: Assume that the rate at which the gas flows out of the box is proportional to the star formation rate:
  - $g(t) = c\, dM_s/dt$ (c is a constant; $c = 0.01 - 5$)
  - As before $dZ/dt = y * (dM_s/dt) / M_g(t)$
  - Where $dM_s/dt = -[1/(1+c)]\, dM_g/dt$
  - So $dZ/dt = -[y/(1+c)] * [1/M_g] * dM_g/dt$
  - Integrating this equation, we get $Z(t) = Z(0) - [y/(1+c)] * \ln[M_g(t)/M_g(0)]$
  - The only effect of an outflow is to reduce the yield to an effective yield $= y/(1+c)$

Veilleux

Veilleux

Accreting-Box Model

- *Example:* Accretion of pristine (metal-free) gas to the box
- Since the gas accreted is pristine, Eq (2) is still valid: the mass of heavy elements produced in a SF episode is

  $dM_h/dt = (y - Z)\, dM_s / dt$

- However, Eq. (1) for the conservation of mass in the box becomes:

  $dM_g/dt = - dM_s/dt + f(t)$

- Consider the simple case in which the mass in gas in the box is constant. This implies then

  $dZ/dt = 1/M_g * [(y - Z)\, dM_s/dt - Z\, dM_g/dt] = 1/M_g * [(y - Z)\, dM_s/dt]$

Accreting-Box Model

- *Integrating and assuming that* $Z(0) = 0$

  $$Z = y\,[1 - e^{-M_s/M_g}]$$

- *Therefore when* $M_s >> M_g$, *the metallicity* $Z \sim y$
- *The mass in stars that are more metal-poor than* Z *is*

  $$M_s(< Z) = -\,M_g \ln(1 - Z/y)$$

- *In this case, for* $M_g \sim 10\ M_{sun}/pc^2$ *and* $M_s \sim 40\ M_{sun}/pc^2$, *and for* $Z = 0.7\ Z_{sun}$, *then* $y \sim 0.71\ Z_{sun}$. *Thus the fraction of stars more metal-poor than* $0.25\ Z_{sun}$ *is* $M(<0.25)/M(<0.7) \sim 10\%$, *in much better agreement with the observations of the solar neighborhood*

Veilleux

Other Solutions

Outflow/Inflow

- Following Mould 1984

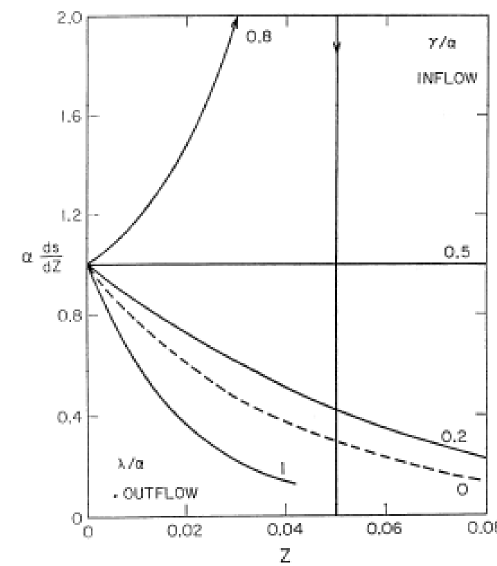
μ is mass of gas, and M_s is the total mass of stars ever made. A fraction α of these consists of long-lived stars (no SN or winds), y is the yield

$Z = y\ln(1/\mu)$; integrating over μ $\langle Z \rangle = y$

- Define an inflow parameter $\gamma dM_s/dt$ pristine material
- outflow $\lambda dM_s/dt$ enriched material
- Conservation of mass gives $\mu = 1 - \alpha M_s + \gamma M_s - \lambda M_s$ as μ goes to zero $Z = y/(1+\lambda/\alpha)$

- The dispersion in metallicity can be shown to be $\sigma_z = (\alpha+\lambda-\gamma)^{0.5}/(\alpha+\lambda+\gamma)^{0.5}$

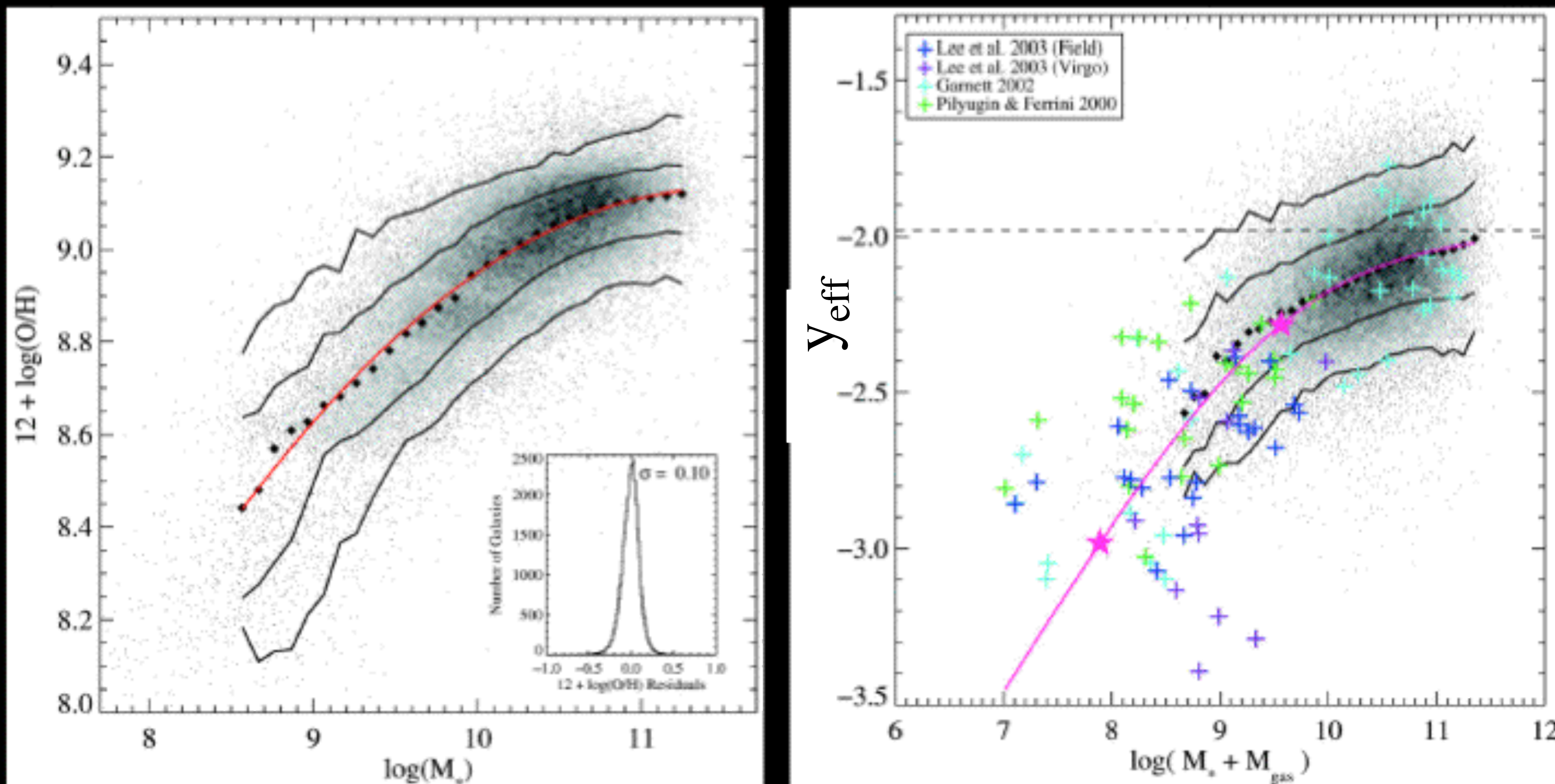
for y=0.04



Local Star-Forming Galaxies

- **Mass-metallicity relation of galaxies favors leaky-box models:**
  → $y_{eff} = [1/(1+c)]\ y$ → winds are more efficient at removing metals from shallower galaxy potential wells ($V_{rot} < 150\ km\ s^{-1}$)

Reminder: $Z(t) = Z(0) - [\ y/(1+c)] * \ln[M_g(t)/M_g(0)]$ (here assume $Z(0) = 0$)



(e.g., Garnett+02; Tremonti+04; Kauffmann+03)

see MBW 11.8.2

Origin of this Relation

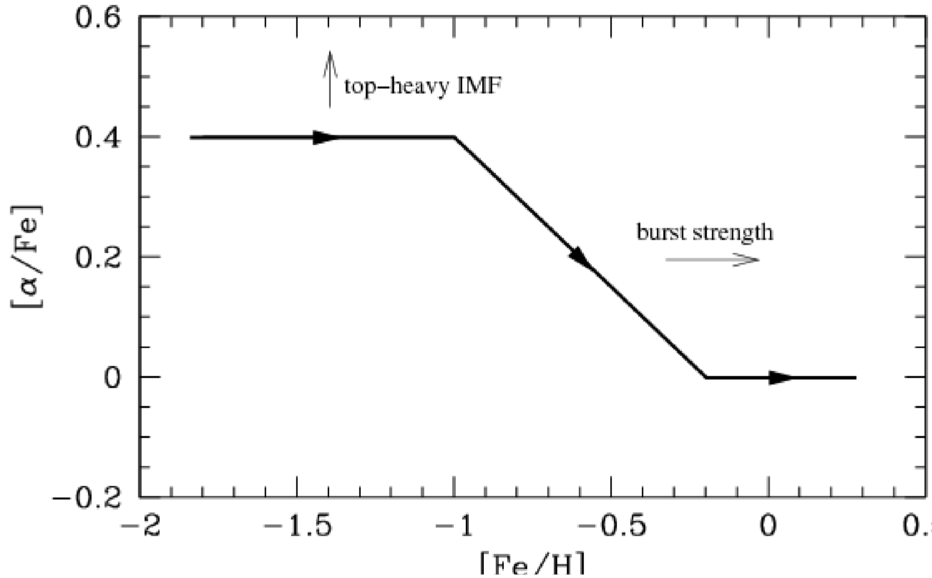
- In closed-box model the metallicity is directly related to the gas mass fraction,
  - less massive disk galaxies have a larger gas mass fraction yes.
- the metallicity–luminosity relation may reflect the impact of inflow and/or outflow.
  - If the infall rate is larger than the star-formation rate, the accreted metal-poor gas will dilute the ISM faster than it can be enriched by evolving stars, thus causing the metallicity to drop.
  - or can lower the metallicity via outflows, but only if the material in the outflow has a higher metallicity than the ISM.
- Thus, inflow and/or outflow can explain the observed metallicity–luminosity relation if effects are higher in lower mass galaxies.
- Use $y_{eff} = Z/\ln(1/f_{gas})$
- Compared to massive spirals, the effective yield in small galaxies is reduced by a factor of several in low-mass galaxies ($V_{rot} \sim< 40$km.s), all of which are relatively gas rich ($f_{gas} > 0.3$).(MWB pg 541)-If the true nucleosynthetic yield is roughly constant among galaxies, then this indicates that low-mass disk galaxies do not evolve as a closed box
- the only mechanism that can explain the extremely low effective yields for low mass disk galaxies is metal-enriched outflows (i.e. outflows with a metallicity larger than that of the gas).MBW pg 542 for detailed explanation

Abundance Ratios-

MBW sec 10.4.4

- While the absolute metallicity assumes constant yields, the relative abundance of the elements gives insight into the stars which produce the metals. (fig 10.10 MBW)
- Notice similarity to pattern of metallicity in MW stars
- MWB state that if the IMF is Saltpeter and the star formation rate is parameterized by a Gaussian of width

  Δt then closed box evolution gives
- log (Δt /Gyr)~1.2-6[α/Fe] (Thomas et al 2005 eq 4; from numerical models) ; (clearly does not work if [α/Fe] >0.2)
- The larger Δt is the lower is the [α/Fe] ratio due to the late time enrichment of Fe due to SNIa; Δt =10Gyrs gives solar abundance



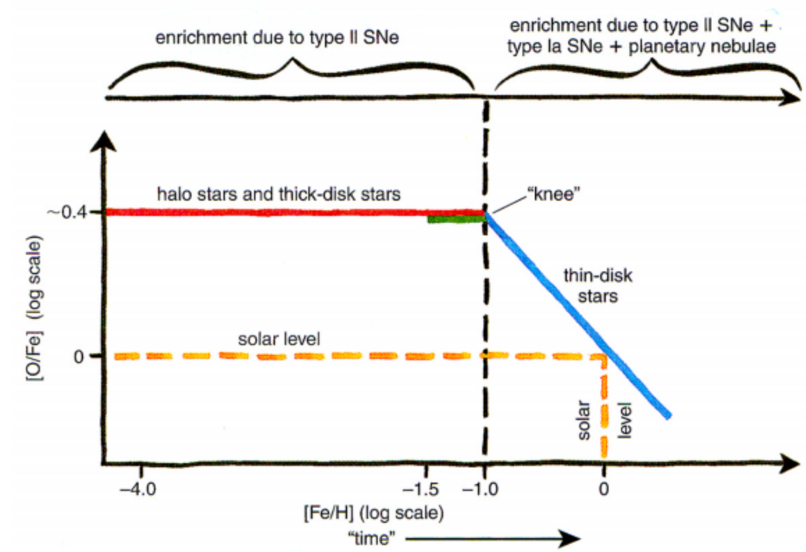
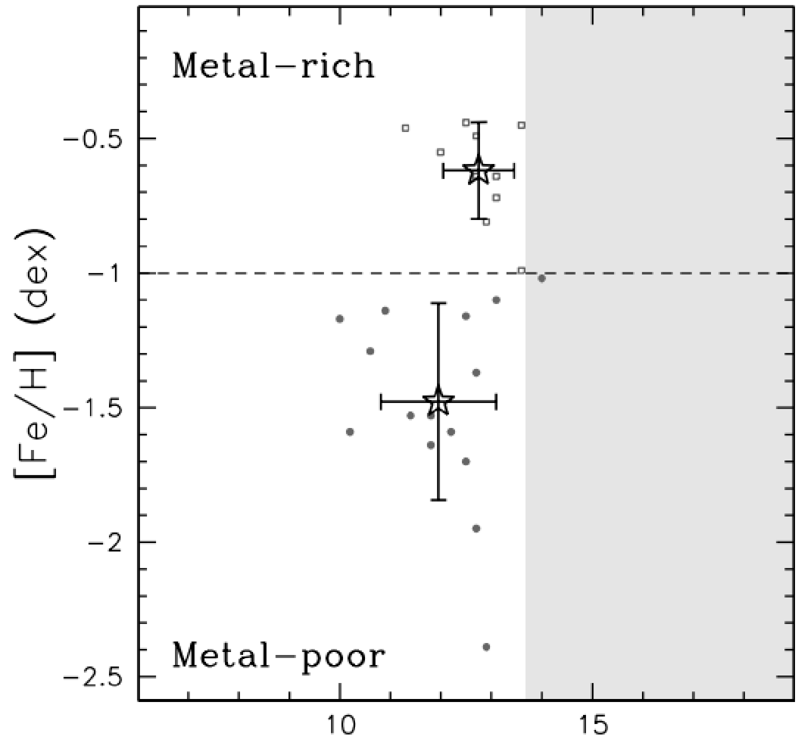
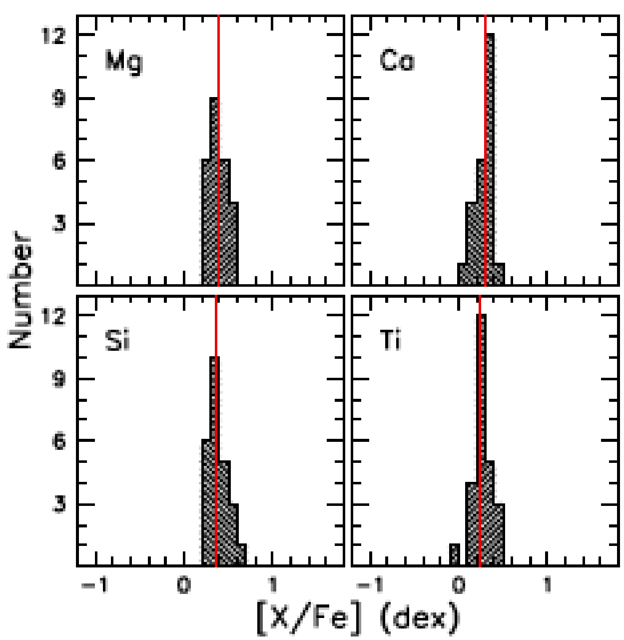


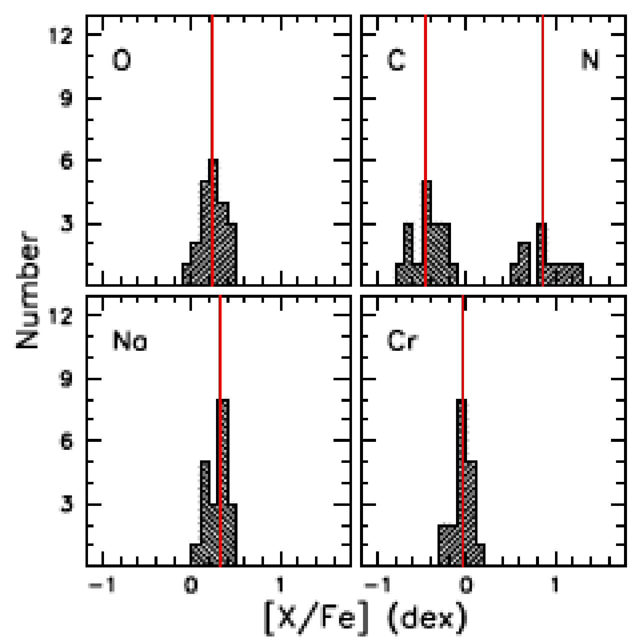
Figure 5. The general metallicity of the Galaxy—as measured by the abundance of iron (Fe), compared with hydrogen (H)—increases with time *(abscissa)* and so serves as a basis for comparing the relative abundances of two elements (such as oxygen (O) and iron; *ordinate*) that are created on different timescales. A plot of these quantities reveals a "plateau" of metal-poor stars (metallicity less than -1) that drops at a "knee" as the relative proportion of iron in the Galaxy increases. Since type Ia supernovae (SNe) are the primary source of iron, astronomers believe that the "knee" occurred about one billion years after the Galaxy began to form *(see Figure 4)*. The halo stars *(red line)* and some of the thick-disk stars *(green line)* tend to occupy the "plateau," whereas thin-disk stars *(blue line)* occupy the descending slope. These observations suggest that the halo, and part of the thick disk were formed in the first billion years of the Galaxy's evolution, and the think disk formed later.

Globular Clusters

- Very different than MW, clusters or galaxies or Local group galaxies
- The age distribution indicates a burst of star formation (12.5-13.0 Gyr ago)
- Using the metallicity and α-element abundances each GC was formed in situ or in a satellite galaxy and subsequently accreted onto the Milky Way (Roediger et al arxiv 1310.3275)
- High abundances (1.7-2.5x solar) indicates that GCs formed rapidly before type Ia's contributed much to the gas (~1 Gyr
- However their remains puzzling patterns in how the different elemental abundances are correlated

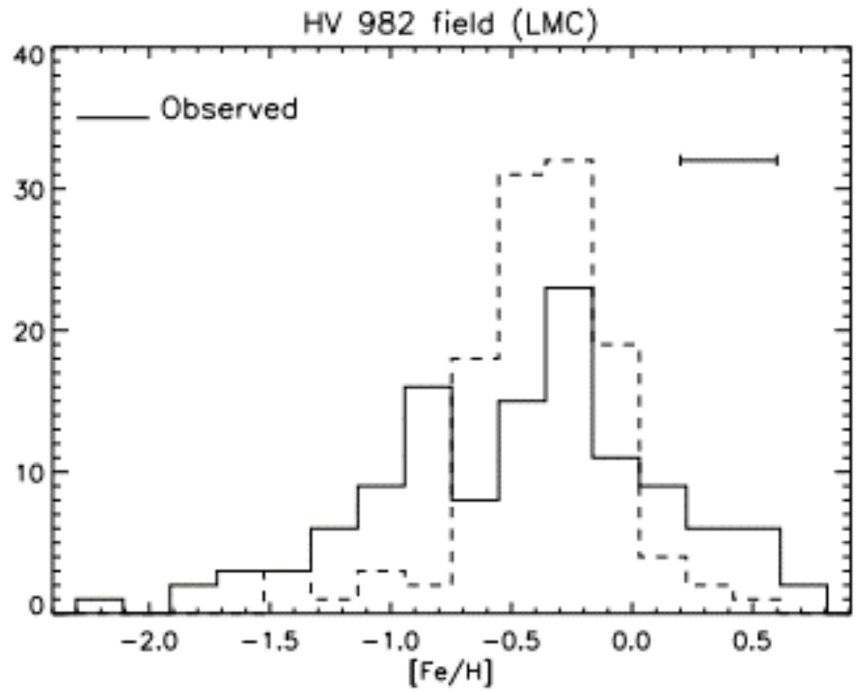


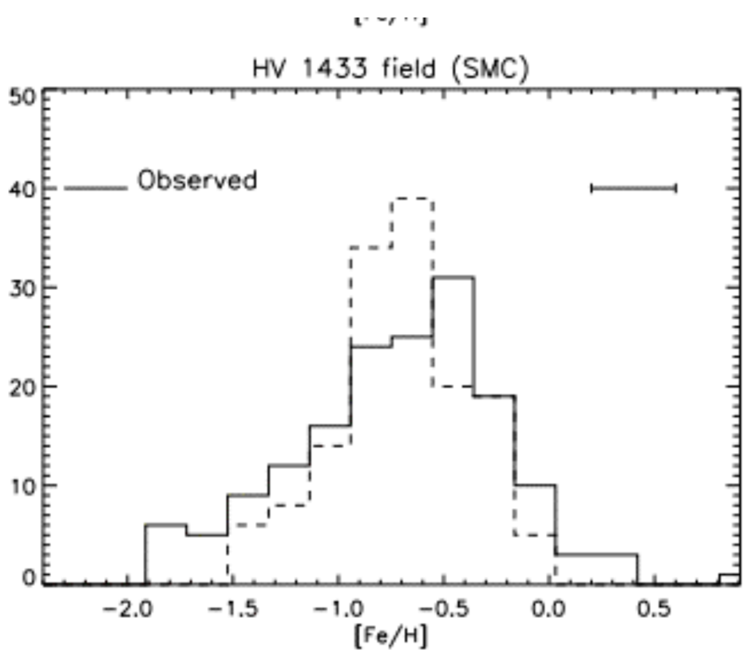




Chemical Evolution

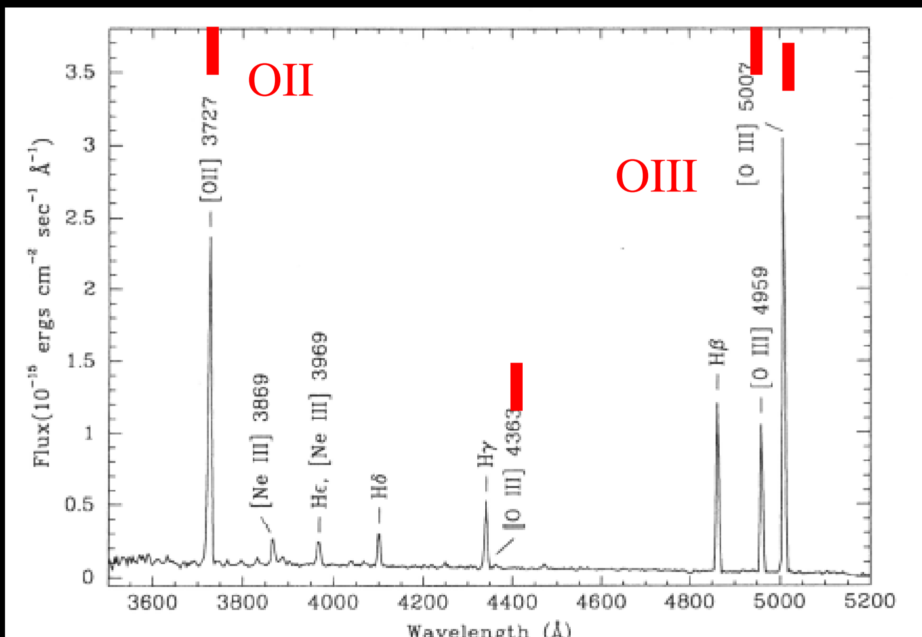
- The one zone no infall or outgo model while analytic (S&Geq 4.13-4.16) does not really represent what has happened
- LMC and SMC are more 'metal poor' than the MW or M31; [Fe/H]~-0.35 and -0.6 respectively - but with considerable variation from place to place.

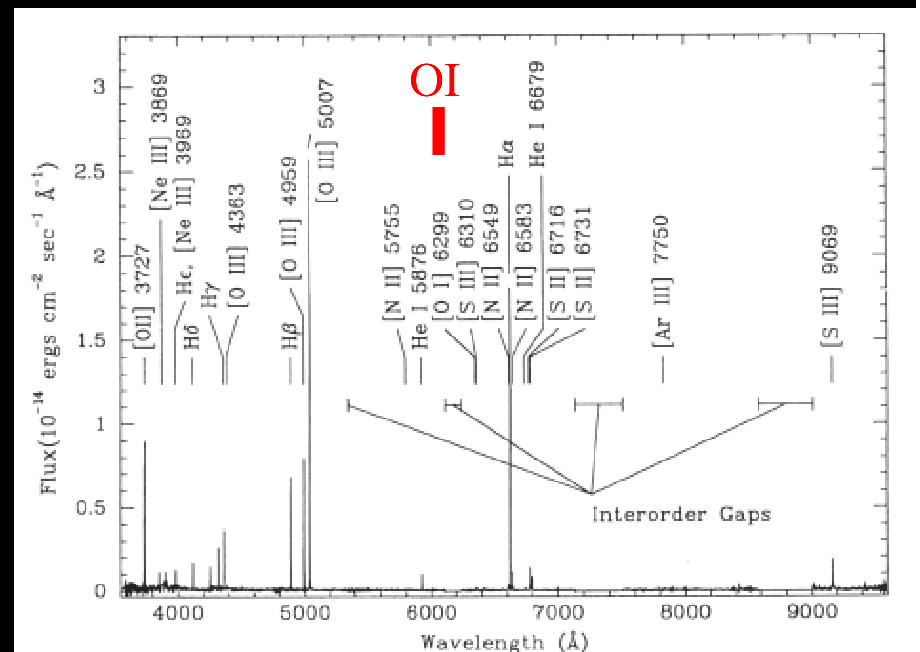




In general line of trend for less massive galaxies to be more metal poor (but large scatter)

Measurements of Oxygen Abundance in Gas Phase





$$O/H = O^o/H + O^+/H + O^{++}/H + \ldots$$

Oxygen is critical to abundance measurements

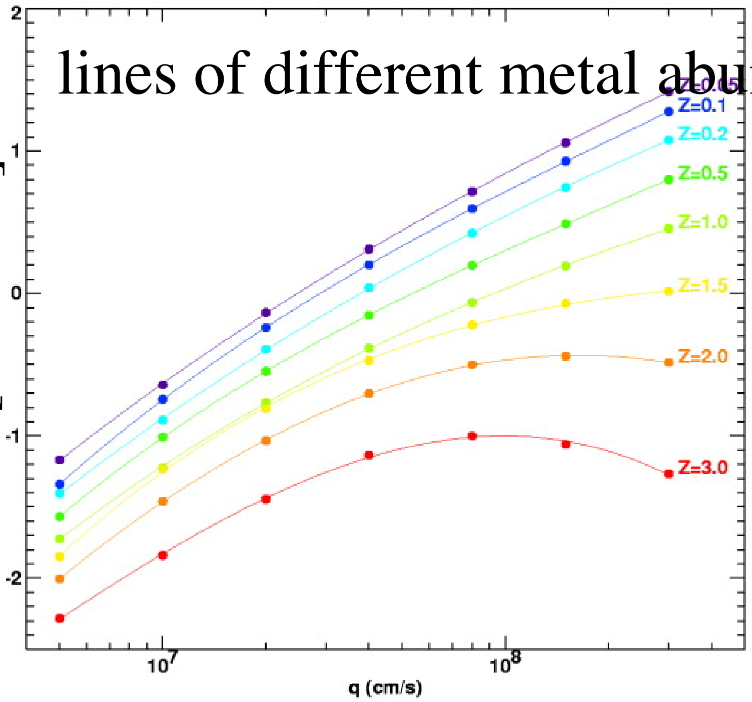
1) relatively easy to measure
2) produce in type IIs so easy to understand
3) the most abundant metals

Calibration of Oxygen Abundance

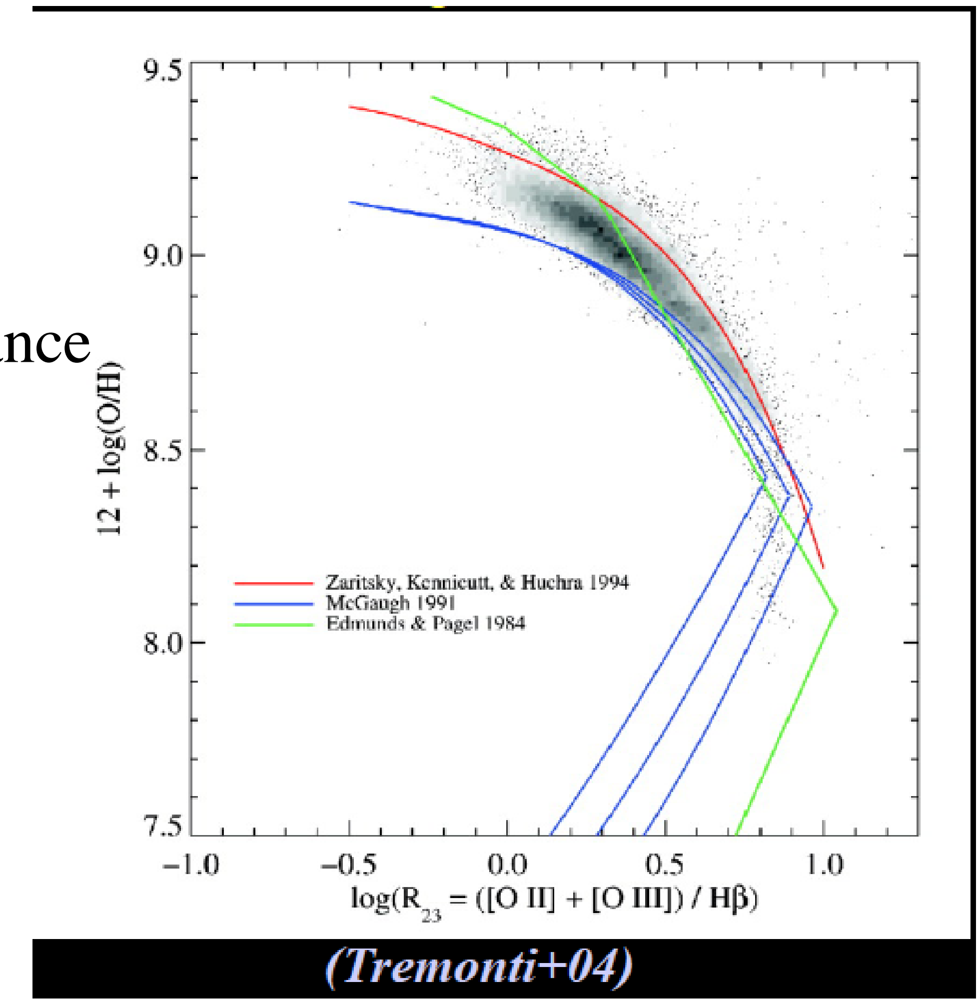
- This relies on photoionization modeling
- Is one uses 'strong' lines (easy to measure) OII OIII need to normalize to hydrogen (Hβ)

[OIII/OII]

lines of different metal abundance



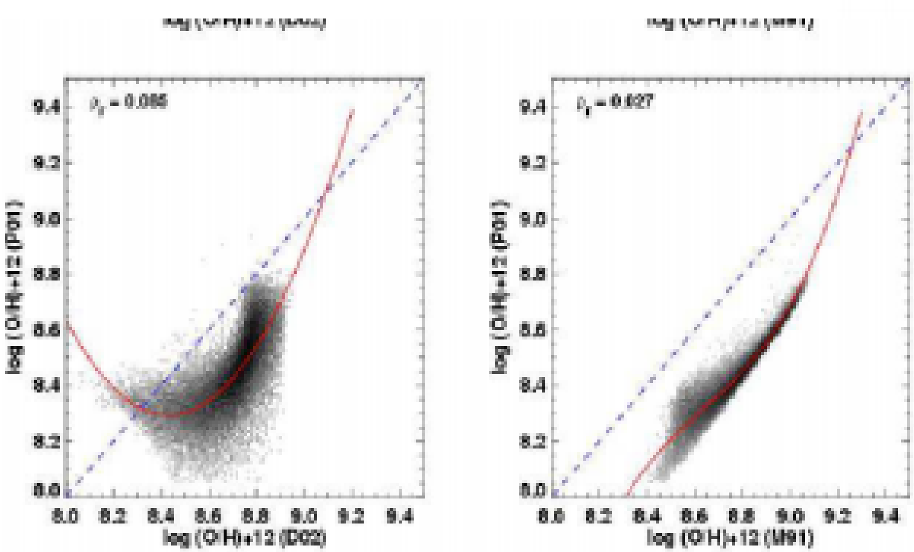
ionization parameter



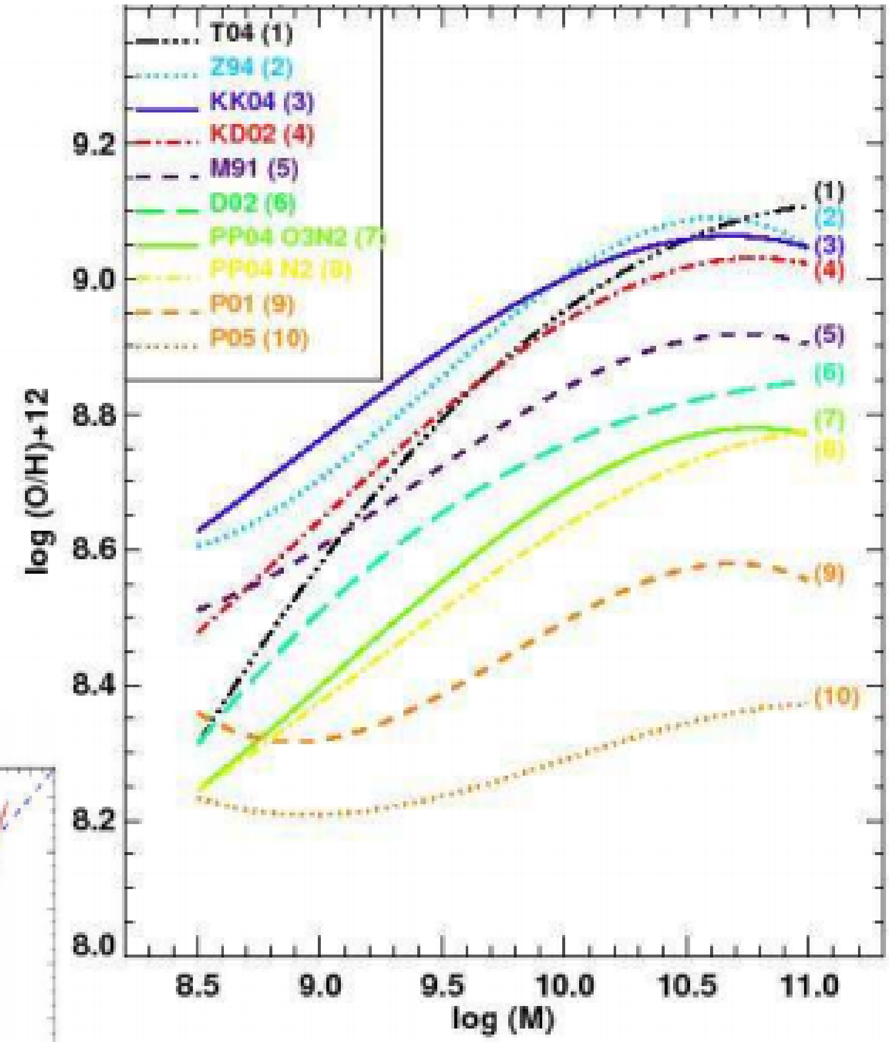
Calibration of Oxygen Abund

- Different techniques can give systematically different answers (Kewley and Ellison 2008)

O abundance method I



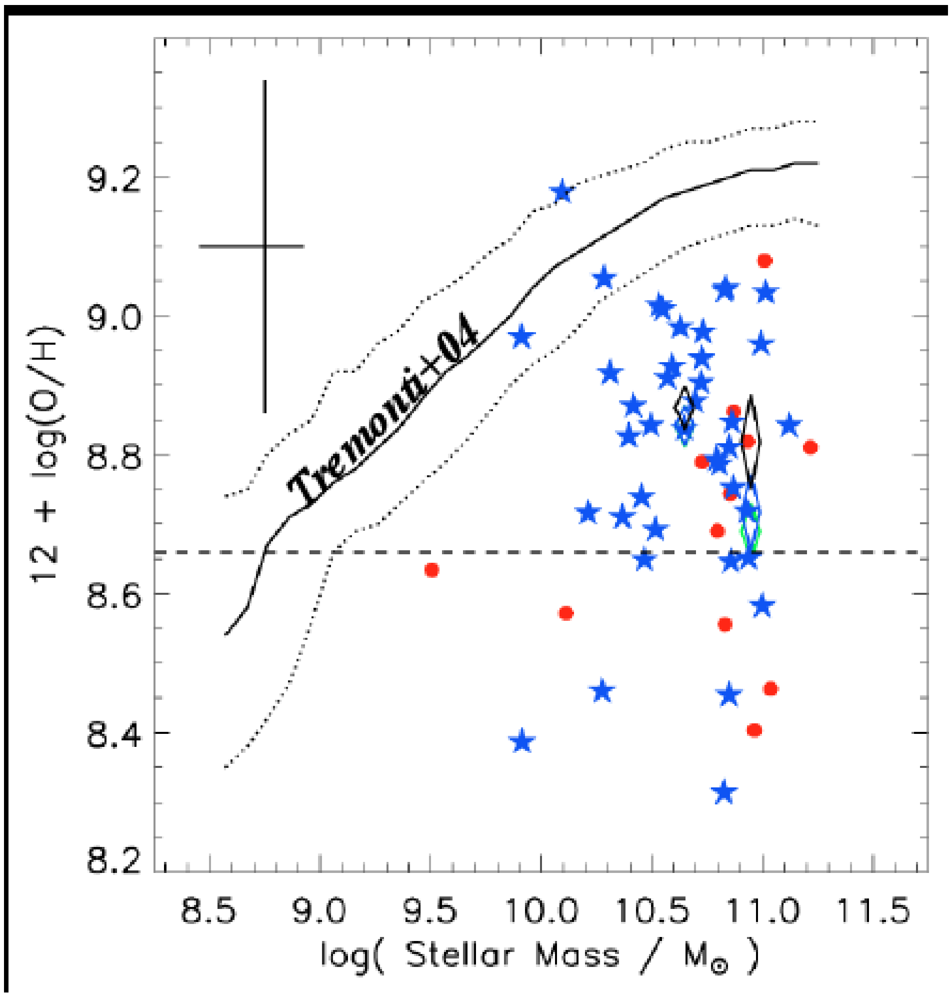
O abundance method II or III



Relation of oxygen abundance to mass for 10 different methods of estimating oxygen abundance

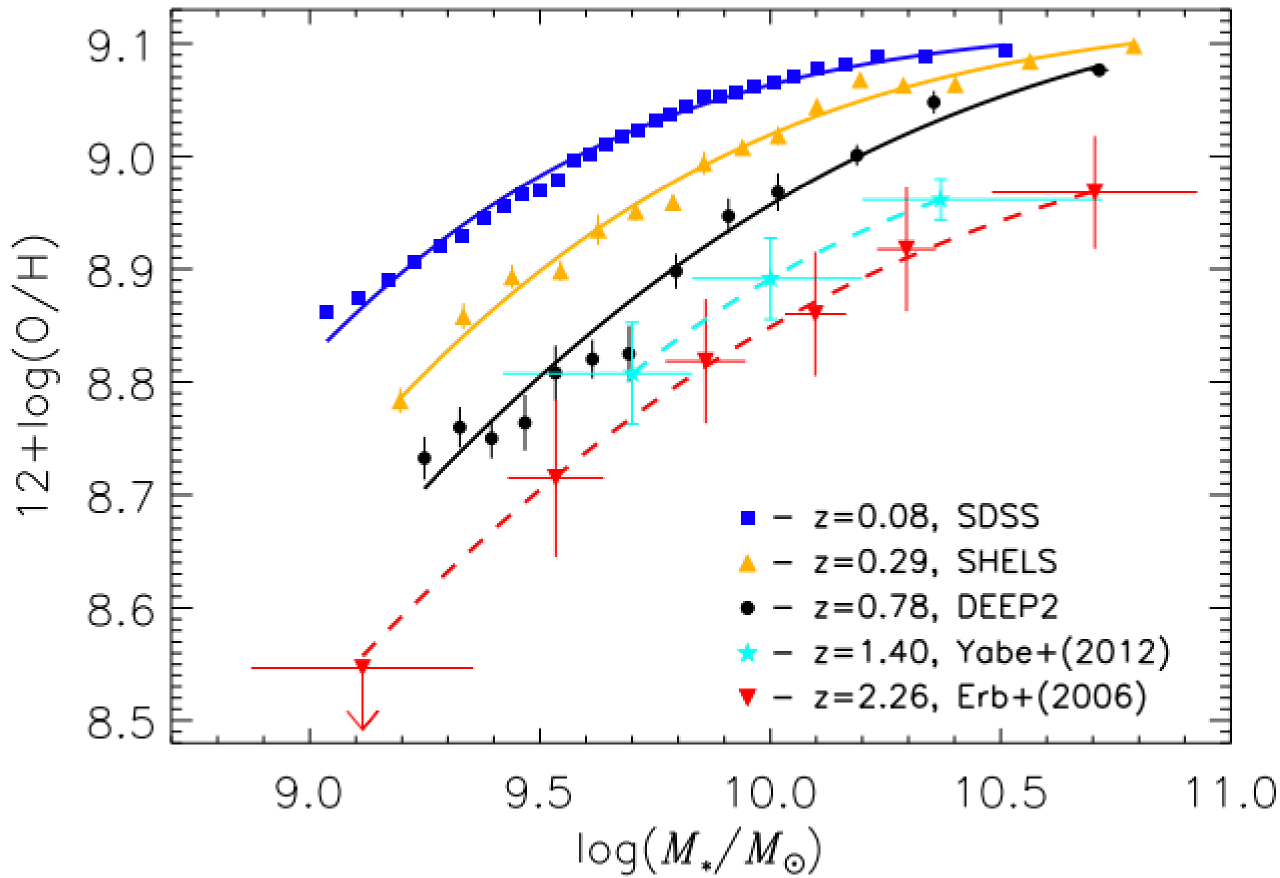
Starbursts

- Oxygen abundance of starbursts lies below that of normal field galaxies- argues for outflow of gas in rapidly star forming galaxies (Rupke,Baker, Veilleux 2008)



Oxygen Evolution

- Mass metallicity evolution
- The metallicities of star-forming galaxi at a fixed stellar ma decrease at all stell mass & 1as a funct redshift.
- However there is a maximal metallicit
- Galaxy metallicitie saturate. The stella mass where galaxy metallicities saturat and the fraction of galaxies with saturated metallicities at a fixed stellar mass evolve



Zahid et al 2013

Summary

- *Simple closed-box model works well for bulge of Milky Way*
- *Outflow and/or accretion is needed to explain*
  - *Metallicity distribution of stars in Milky Way disk*
  - *Mass-metallicity relation of local star-forming galaxies*
  - *Metallicity-radius relation in disk galaxies*
  - *Merger-induced starburst galaxies*
  - *Mass-metallicity relation in distant star-forming galaxies*
  - *Distant quasars*

Calibration of absolute abundances in optical band difficult